Excess Heat Removal from Cylindrical Surrounding-Gate MOSFETs

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As the device feature sizes continue to shrink toward nanometer scale, thermal properties of semiconductor nanostructures gain particular importance [1]. The downscaling trend in electronic devices leads to increase in power dissipation per unit area despite reduction in the power supply voltage. A variety of size effects that manifest themselves at nanoscale may adversely affect the lattice thermal conductivity of nanostructured materials [2].

In this talk we argue that the excess heat removal may become a particularly serious problem for recently proposed cylindrical surrounding-gate MOSFETs. Vertical, cylindrical surrounding-gate MOSFETs have emerged as a new possible alternative technology to the traditional planar transistors with the goal of achieving higher packing densities and overcoming such drawbacks as short-channel effects and poor sub-threshold characteristics [3]. Vertical surrounding-gate MOSFETs are fabricated on a cylindrical pillar of silicon with the lateral dimensions that currently can go down to 50 nm. Thermal conductivity of the gate oxide that surrounds a silicon pillar is much smaller than that of the silicon. Thus, bulk of excess heat has to flow along the pillar until reaching a heat sink. Thermal conductivity of the silicon nanometer size pillars, e.g. nanowires, may be significantly different from that of bulk silicon. This change has to be taken into account while considering device reliability issues and simulating device operation.

We will present a self-consistent model for calculating the lattice thermal conductivity in semiconductor nanowires. The model is based on the solution of phonon Boltzmann equation with given boundary conditions. It takes into account modification of the acoustic phonon dispersion in low-dimensional structures with the lateral feature size of 10 nm – 30 nm, and change in the non-equilibrium phonon distribution due to partially diffuse scattering from rough boundaries and interfaces. The diffusive boundary scattering means that phonons can scatter from the interface at any direction irrespective of the angle of the incident phonon.

The feature size of the structures under consideration is significantly smaller than the acoustic phonon mean free path (MFP) and approaches the thermal phonon wavelength (the room temperature MFP in silicon is about 260 nm calculated using the kinetic theory with dispersion). At such length scale the phonon dispersion modification effects on thermal conductivity are expected to be particularly strong. It will be shown that the presence of the distinctive boundaries in such structures leads to a transformation of the acoustic branches of phonon dispersion to a set of one quasi-acoustic mode and a number of quasi-optical modes, which are characterized by a low group velocity and cut-off frequencies. This transformation affects both in-plane and cross-plane thermal conduction in low-dimensional structures.

Once we have found the functional dependence of phonon group velocity on phonon energy [4] we calculate the phonon relaxation rates. The results are then used to calculate lattice thermal conductivity. Figure 1 shows the lattice thermal conductivity as a function of parameter p for a nanowire with the diameter D=20 nm. The value of p represents the probability that the phonon is undergoing a specular scattering event at the interface, which does not contribute to the boundary thermal resistance. The value of 1-p represents the probability that the phonon is undergoing a diffuse scattering event. Our results indicate that *the bulk value is not recovered* even in the case of purely specular scattering due to the modification of the phonon dispersion and corresponding decrease of the phonon group velocity for given nanowire size and boundary conditions. It is also established that inclusion of the phonon redistribution effects together with phonon confinement, e.g. dispersion modification, leads to a significant overall reduction in the lattice thermal conductivity in a nanowire. The data presented in Figure 1 is given for the case of complete acoustic phonon mode confinement at the boundary of the nanowire, e.g. silicon pillar, thus providing the lower limit for the thermal conductivity.

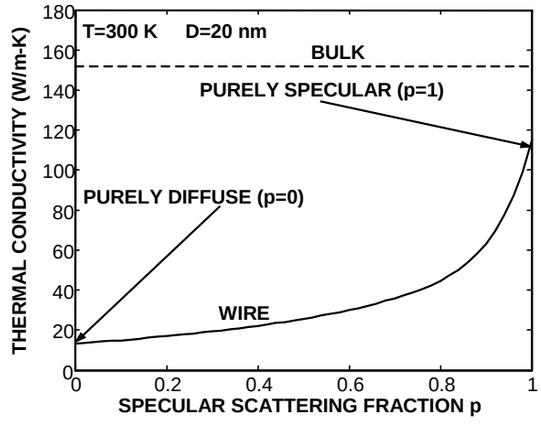

Figure 1. Lattice thermal conductivity as a function of specular scattering fraction p calculated in a free-standing silicon cylindrical nanowire of diameter D=20 nm.

The described changes in phonon transport in semiconductor nanowires bear important consequences for vertical device simulation. The observed modification of the thermal resistance has to be taken into account in simulation of excess heat removal from cylindrical surrounding-gate MOSFETs since it strongly affects the electrostatic discharge voltage (ESD) and other reliability characteristics.

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